Sequential design for detecting masked and self masked failure modes

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Abstract

Failure modes with masked, slow kinetics are the bane of reliability engineers. A masked failure mode in a "typical" accelerated test never shows up, either because another failure mode completely censors it at the (usually) highly accelerated test conditions, or because the failure kinetics/physics is self-masking. The masking failure mode, if present, is often irrelevant at operating conditions. If the masked failure mode is relevant at operating conditions, this can cause significant loss.
There are two situations one can be in with respect to masked failure modes.

i) A masked or self-masking failure mode has appeared in operation, and the problem is to identify what part of the population is at risk and develop a screening procedure.
ii) The device/material system is still in qualification, and the question is to determine what risk there is of a masked or self-masking failure mode.

In this paper sequential experimental strategies appropriate to each of these situations are developed.

1. Introduction

The risk of fielding either a totally new technology, or an existing technology in a new environment, is that there is always the possibility of there being a previously unlooked for failure mode making a rout of the introduction. Examples range from the dramatic (the Challenger disaster) to the subtle (stress voiding in aluminium lines in integrated circuits under storage conditions). The consequences can also have a wide range, from early failure in a battery of a child's toy, to the misfiring of an automatic weapon in a soldier's hands.
Most experienced reliability hands will tell you that the problems typically arise not from failure modes that are studied in extreme detail, but from those not thought of or looked for. Thus what is really needed is a methodology that focuses attention on failure modes that are either totally unthought of, masked, or mask themselves in the usual tests. The failure modes that are totally unthought of typically are accelerated by "unusual" stresses. Thus to be 100% sure of spotting them requires some kind of surveillance on product in the field. Interestingly, this is also true for masked and self-masking failure modes. Thus extremely high reliability cannot be assured by accelerated testing alone. Field tracking, and contingency plans for unexpected failure modes are necessary.
This result has implications for example for the Yucca Mountain storage facility (Ewing and MacFarlane, 2002). A system of surveillance, with effective cleanup procedures has to be in place to minimize the risk of damage to the local area by leakage. Similarly, projects such as fertilizing the southern oceans with iron to increase biomass production and reduce CO_2 in the atmosphere (Buesseler et. Al, 2004) may require appropriate monitoring and action plans.
In this paper, we focus on masked and self-masked failure modes, for much simpler dynamics. In particular, we consider the simplest failure mode (where masking can occur), and the simplest self-

masking failure mode, using the Arrhenius approximation (Benson, 1960) for the temperature dependence of the rate constants.
In the next section, the two models we examine are developed. In the third section, a qualification program is examined from the point of view of how information accumulates on relevant failure modes over time through kinetic calculation. In the fourth section, it is shown how analytical demarcation maps (LuValle et. Al, 1998) can be used in conjunction with such a qualification program to quickly nail down experimental regimes for studying new failure modes appearing in the field.
In both cases, the approach is to solve the problem from the viewpoint of what models are plausibly identifiable by a given set of experiments (particularly if no failures occur).

2. Two simple models

In this section we assume that the rate-limiting chemical processes are all well approximated by the Arrhenius model, and that the kinetics of the process is best approximated by one of two schemes. More realistically, one would use a properly constructed evanescent process map (LuValle, LeFevre and Kannan, 2004, LuValle, 2004) to evaluate the apriori value of an experiment, but here we are trying to simplify as much as possible. The two schemes are:

$$1)\quad A_1 \xrightarrow{k_1} A_2,\ k_1 = \nu_1 \exp\left(-E_{a1}/kT\right) : \frac{dA}{dt} = \begin{pmatrix} -k_1 & 0 \\ k_1 & 0 \end{pmatrix} A,\ A_{2t} = A_{10}\left(1-\exp\left(-k_1 t\right)\right),\ A_{t=0} = \begin{pmatrix} A_{10} \\ 0 \end{pmatrix}$$

$$2)\quad A_1 \begin{array}{l} \xrightarrow{k_1} A_2, k_1 = \nu_1 \exp\left(-E_{a1}/kT\right) \\ \xrightarrow{k_2} A_3, k_2 = \nu_2 \exp\left(-E_{a2}/kT\right) \end{array} : \frac{dA}{dt} = \begin{pmatrix} -\left(k_1+k_2\right) & 0 & 0 \\ k_1 & 0 & 0 \\ k_2 & 0 & 0 \end{pmatrix} A,$$

$$A_{2t} = \frac{A_{10}k_1\left(1-\exp\left(-\left(k_1+k_2\right)t\right)\right)}{k_1+k_2},\ A_{t=0} = \begin{pmatrix} A_{10} \\ 0 \\ 0 \end{pmatrix}$$

We assume that failure (or noticeable degradation) is caused by A_2 rising above a certain device specific value, and that device specific value is independent of stress.
For statistical interpretation, in the case of no failures occurring (our optimistic and hoped for outcome) our best description of the data is a binomial distribution (presence or absence of a failure) in a Bayesian structure (LuValle, 2004). We assume a prior with support in activation energy from >0 to 3 electron volts, and in $\log_{10}(\nu)$, from –10 to 20, where ν is measured in Hertz. This seems a rather wide range, but in fact is reasonable for life times up to 50 years. The upper bound of 10^{20} Hertz is reasonable for electronic processes over short range in solid state, while the lower bound is a bit lower than the slowest possible reaction that can occur over 50 years.
For the purpose of numerical evaluation, we approximate the range of $\log_{10}(\nu)$ with 16 equally spaced points and the range of activation energies with 15 equally spaced points. Thus for the first scheme shown above, for each experiment the corresponding differential equation has to be evaluated 240 times, and for the second scheme, 57600 times. Since both equations are monotone increasing in A_2, we simply have to compare the ending amount of A_2 in the experiment, and in life, at a particular parameter vector to

determine if the experiment has proceeded beyond end of life for that parameter vector. If it has, then for that parameter vector, no failure in experiment indicates no failure in life for the same device.

3. Evaluating expected information accumulation in a sequential qualification scheme

Table 1 below shows a sequence of experiments in a proposed qualification plan, starting with an experiment at 80 °C for 100 hours, and ending with one at 40 °C for 50 years (the assumed lifetime of the product). The experiments are arranged in order of increasing duration, and within that, decreasing temperature. Columns 4 and 5 show the proportion of parameter vectors in the life experiment that are covered by the experiment at hand, and the incremental information that this experiment provides over those proceeding them in the table, in terms of that percent of parameters.
The results for scheme 1 square well with the usual intuition most engineers use with accelerated testing. That is that the lower temperature experiments running for the same time offer no additional information over the experiments run at higher temperatures. On the other hand, with scheme 2 (a perfectly plausible scheme for a chemical kinetic process) more information is added by running lower temperature schemes. This is most exaggerated by comparing experiments 10 and 11, fully 7 percent of the plausible process that can occur in life will not show up in a test running for the same time period 10 °C hotter.

Table 1: Incremental coverage of kinetic models for life (50 years 40 °C) for qualification sequence of experiments assuming no failures

Experiment Number	Temperature	Time	(Incremental) Proportion of life covered scheme 1	(Incremental) Proportion of life covered scheme 2
1	80	100	0.60 (0.60)	0.64 (0.64)
2	70	100	0.4 (0.0)	0.48 (0.0026)
3	80	1000	0.75 (0.15)	0.74 (0.11)
4	70	1000	0.62 (0.0)	0.65 (0.00057)
5	60	1000	0.33 (0.0)	0.44 (0.0013)
6	70	8760 (1 yr)	0.81 (0.06)	0.79 (0.048)
7	60	8760 (1 yr)	0.68 (0.0)	0.70 (0.0013)
8	60	87600 (10 yrs)	0.93 (0.12)	0.88 (0.089)
9	50	87600 (10 yrs)	0.76 (0.0)	0.75 (0.00083)
10	50	438000 (50 yrs)	1.0 (0.07)	0.93 (0.048)
11	40	438000 (50 yrs)	1.0 (0.0)	1.0 (0.064)

Interestingly, the lower the temperature, the higher the incremental proportion (compare experiments 3,4, and 5). To test that, the calculation was made adding in a 1 year 40 °C experiment. The incremental proportion inserting it in as experiment 7.5 is 0.033, larger than the 60 °C experiment as indicated.

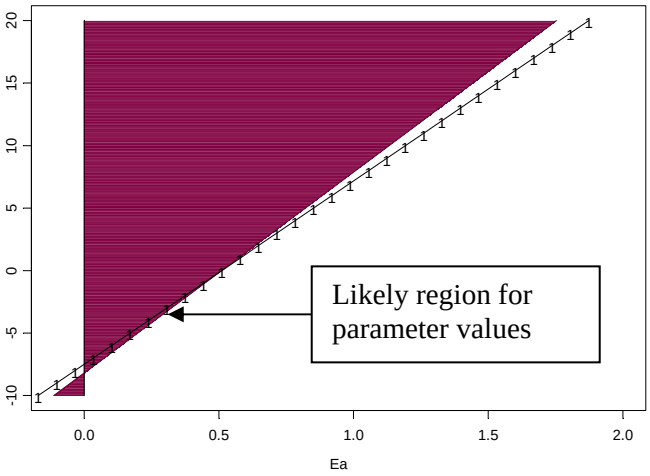
4. Using information from the qualification scheme to evaluate failures

Suppose that the above scheme is implemented on a device where testing for failure is a destructive intervention (e.g., part of an armament where the armament has to be detonated to test functionality) and a failure occurs in the field at 5 years at 40 °C, with no failures prior in the testing program. Withdrawing some devices from experiments 8 and 9 for early testing shows failures consistent with scheme 1. Then we can narrow down the plausible set of parameters under scheme 1 for ν and E_a by using analytical

demarcation maps (LuValle et. Al, 1998). This gives us a quick approximation to what temperatures and times might be necessary to duplicate the failures, in a manner which will give us precise estimates of the parameters. For the Arrhenius approximation, analytical demarcation maps are constructed by the surprisingly useful expedient of substituting an indicator function for the exponential function in scheme 1 above. The indicator is $1 \text{ if } k_1 t \geq 1,\ 0 \text{ o.w.}$

This allows us to derive: $t\nu \exp\left(-\frac{E_a}{kT}\right) = 1$ or $E_a = kT \ln(\nu t)$. The latter equation describes a front in parameter space of the equations corresponding to "completion" of the process. Figure 1 below shows the fronts for 40 °C for 5 years (front marked by the red region to the left of it) and the front for 1 year at 70 °C (the number 1 decorates the line). The horizontal axis shows activation energy in electron volts (eV), the vertical $\log_{10}(\nu)$ with ν in Hertz. Ignore the region to the readers left of the line corresponding to 0 eV activation energy. The region where the failures most likely are occurring is the small triangle pointed to in the figure, in front of the 70 °C front for 1 year, and behind the 40 °C front for 5 years.

Figure 1



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